

This Page Is Inserted by IFW Operations
and is not a part of the Official Record

BEST AVAILABLE IMAGES

Defective images within this document are accurate representations of the original documents submitted by the applicant.

Defects in the images may include (but are not limited to):

- BLACK BORDERS
- TEXT CUT OFF AT TOP, BOTTOM OR SIDES
- FADED TEXT
- ILLEGIBLE TEXT
- SKEWED/SLANTED IMAGES
- COLORED PHOTOS
- BLACK OR VERY BLACK AND WHITE DARK PHOTOS
- GRAY SCALE DOCUMENTS

IMAGES ARE BEST AVAILABLE COPY.

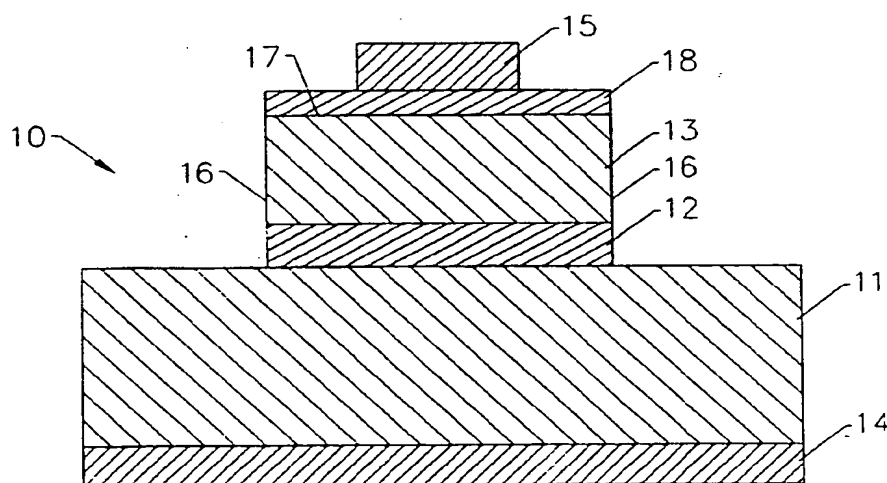
**As rescanning documents *will not* correct images,
please do not report the images to the
Image Problem Mailbox.**

THIS PAGE BLANK (USPTO)

PCTWORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification ⁵ : H01L 33/00	A1	(11) International Publication Number: WO 95/00974 (43) International Publication Date: 5 January 1995 (05.01.95)
(21) International Application Number: PCT/US94/04497 (22) International Filing Date: 22 April 1994 (22.04.94) (30) Priority Data: 081,668 23 June 1993 (23.06.93) US (60) Parent Application or Grant (63) Related by Continuation US 081,668 (CON) Filed on 23 June 1993 (23.06.93) (71) Applicant (for all designated States except US): CREE RE- SEARCH, INC. [US/US]; Suite 176, 2810 Meridian Park- way, Durham, NC 27713 (US). (72) Inventors; and (75) Inventors/Applicants (for US only): EDMOND, John, A. [US/US]; 1310 Boxwood Lane, Apex, NC 27502 (US). KONG, Hua-Shuang [CN/US]; 10840 Bexhill Drive, Raleigh, NC 27606 (US). (74) Agents: SUMMA, Philip et al.; Bell, Seltzer, Park & Gibson, P.O. Drawer 34009, Charlotte, NC 28234 (US).		(81) Designated States: AT, AU, BB, BG, BR, BY, CA, CH, CN, CZ, DE, DK, ES, FI, GB, GE, HU, JP, KG, KP, KR, KZ, LK, LU, LV, MD, MG, MN, MW, NL, NO, NZ, PL, PT, RO, RU, SD, SE, SI, SK, TJ, TT, UA, US, UZ, VN, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG). Published <i>With international search report.</i>

(54) Title: BLUE LIGHT-EMITTING DIODE WITH HIGH EXTERNAL QUANTUM EFFICIENCY**(57) Abstract**

A light emitting diode is disclosed that emits light in the blue portion of the visible spectrum with high external quantum efficiency. The diode comprises a single crystal silicon carbide substrate having a first conductivity type, a first epitaxial layer of silicon carbide on the substrate and having the same conductivity type as the substrate, and a second epitaxial layer of silicon carbide on the first epitaxial layer and having the opposite conductivity type from the first layer. The first and second epitaxial layers forming a p-n junction, and the diode includes ohmic contacts for applying a potential difference across the p-n junction. The second epitaxial layer has side walls and a top surface that forms the top surface of the diode, and the second epitaxial layer has a thickness sufficient to increase the solid angle at which light emitted by the junction will radiate externally from the side walls, but less than the thickness at which internal absorption in said second layer would substantially reduce the light emitted from said top surface of the diode.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AT	Austria	GB	United Kingdom	MR	Mauritania
AU	Australia	GE	Georgia	MW	Malawi
BB	Barbados	GN	Guinea	NE	Niger
BE	Belgium	GR	Greece	NL	Netherlands
BF	Burkina Faso	HU	Hungary	NO	Norway
BG	Bulgaria	IE	Ireland	NZ	New Zealand
BJ	Benin	IT	Italy	PL	Poland
BR	Brazil	JP	Japan	PT	Portugal
BY	Belarus	KE	Kenya	RO	Romania
CA	Canada	KG	Kyrgyzstan	RU	Russian Federation
CF	Central African Republic	KP	Democratic People's Republic of Korea	SD	Sudan
CG	Congo	KR	Republic of Korea	SE	Sweden
CH	Switzerland	KZ	Kazakhstan	SI	Slovenia
CI	Côte d'Ivoire	LI	Liechtenstein	SK	Slovakia
CM	Cameroon	LK	Sri Lanka	SN	Senegal
CN	China	LU	Luxembourg	TD	Chad
CS	Czechoslovakia	LV	Latvia	TG	Togo
CZ	Czech Republic	MC	Monaco	TJ	Tajikistan
DE	Germany	MD	Republic of Moldova	TT	Trinidad and Tobago
DK	Denmark	MG	Madagascar	UA	Ukraine
ES	Spain	ML	Mali	US	United States of America
FI	Finland	MN	Mongolia	UZ	Uzbekistan
FR	France			VN	Viet Nam
GA	Gabon				

BLUE LIGHT-EMITTING DIODE WITH HIGH EXTERNAL QUANTUM EFFICIENCY

Field of the Invention

The present invention relates to light-emitting diodes, and in particular relates to blue light-emitting diodes formed in silicon carbide.

5 Background of the Invention

Light-emitting diodes, commonly referred to as "LED's" are semiconductor devices which convert electrical energy into emitted light.

As is known to those familiar with atomic and
10 molecular structure of semiconductor materials and electronic devices, electromagnetic radiation, including visible light, is produced by electronic transitions that occur in atoms, molecules, and crystals. Furthermore, the color of light that can be
15 produced from an LED is a function of the basic semiconductor material from which the LED is formed, and the manner in which the semiconductor material may be doped. As is further known to such persons, blue light represents one of the higher energy phenomena
20 within the spectrum visible to the human eye. By way of comparison, higher energy transitions such as ultraviolet light are invisible to the human eye. Similarly, red light represents the lower energy end of the visible spectrum, and infrared, far infrared, and
25 microwave radiation represent even lower energy transitions that are out of the range of the visible spectrum.

Only certain semiconductor materials have the capability to permit the type of electronic transitions
30 that will produce blue light in the visible spectrum.

-2-

One of these materials is silicon carbide (SiC) which can produce several different wavelengths of blue light. The characteristics of silicon carbide and the manner in which blue light can be produced using silicon carbide are thoroughly discussed in U.S. Patents Nos. 4,918,497 and 5,027,168, both entitled "Blue Light-Emitting Diode Formed in Silicon Carbide." Both of these patents are assigned to the assignee of the present application. These patents are incorporated entirely herein by reference ("the '497 and '168 patents").

The increased availability of blue LEDs has, however, increased both the demand for the devices and for particular performance specifications. In particular, one important performance characteristic of an LED is the amount of light it can produce from a given amount of electricity, a relationship referred to as quantum efficiency. As the use of blue LEDs has increased, the demand for LEDs with higher quantum efficiencies has likewise increased.

There are, however, some particular aspects of silicon carbide which must be addressed when attempting to increase the quantum efficiency.

LEDs formed in more conventional materials such as gallium phosphide (GaP) provide a comparative example. Gallium phosphide's conductivity is generally sufficient for the entire device to light up as current passes across the p-n junction. Stated differently, current spreads relatively easily in gallium phosphide, thus spreading the generated light relatively easily as well. For lower conductivity materials such as p-type silicon carbide, however, the current does not spread as efficiently throughout the entire device, thus reducing the amount of emitted light that could otherwise be generated.

The conductivity of silicon carbide can be increased, of course, by increasing its dopant

-3-

concentration. Increasing the doping level is a less desirable solution, however, because the increased doping lowers the transparency of the device, thus detracting from its overall performance.

- 5 Furthermore, producing a blue LED in silicon carbide requires various dopant and current injection considerations in a manner described thoroughly in the '497 and '168 patents.

Object and Summary of the Invention

- 10 Accordingly, it is an object of the present invention to provide a light-emitting diode that emits light in the blue portion of the visible spectrum with a relatively high external quantum efficiency.

- In one embodiment, the invention comprises an
15 LED in which the top epitaxial layer has a thickness sufficient to increase the solid angle at which light emitted by the junction will radiate externally from the side walls of the layer, but less than the thickness at which internal absorption in the layer
20 would substantially reduce the light emitted from the top surface of the diode.

In another embodiment, the invention comprises increasing the surface area of the top surface of the light-emitting diode.

- 25 In another embodiment, the invention comprises using a metal ohmic contact that will form a reflective surface from which light generated by the diode will reflect rather than be absorbed.

- In yet another embodiment, the invention
30 comprises a method of forming a reflective ohmic contact on silicon carbide.

- In yet another embodiment, the invention comprises the use of a transparent conductive contact on a blue light-emitting diode formed in silicon
35 carbide.

The foregoing and other objects, advantages and features of the invention, and the manner in which

-4-

the same are accomplished, will become more readily apparent upon consideration of the following detailed description of the invention taken in conjunction with the accompanying drawings, which illustrate preferred and exemplary embodiments, and wherein:

Description of the Drawings

Figure 1 is a cross-sectional schematic view of a first embodiment of a blue LED according to the present invention;

10 Figure 2 is another cross-sectional schematic illustration of a second embodiment of a blue LED according to the present invention;

15 Figure 3 is a plot of relative intensity plotted against wavelength for a blue LED according to the present invention;

Figure 4 is a combination plot of radiant flux in micro-watts and external power efficiency in percentage plotted against forward current in milliamps across the diode;

20 Figure 5 is a plot of light output expressed as a percentage taken against the area of the top surface of the diode measured in mils along each side of a square mesa;

25 Figure 6 is a plot of light output as a percentage taken against the thickness of the top epitaxial layer of blue LEDs according to the present invention and measured in microns;

30 Figure 7 is a second plot of light output as a percentage taken against the thickness of the top epitaxial layer of blue LEDs according to the present invention and measured in microns;

Figure 8 is a plot of the absorption coefficient of silicon carbide as a function of n-type dopant concentration; and

35 Figure 9 is a plot of the absorption coefficient of silicon carbide as a function of p-type dopant concentration.

-5-

Detailed Description

The present invention is a light-emitting diode that emits light in the blue portion of the visible spectrum (i.e., approximately 400-480 nanometers (nm)) with high external quantum efficiency. In a first embodiment illustrated in Figure 1, the blue LED is broadly designated at 10. The diode 10 includes a single crystal silicon carbide substrate 11 having a first conductivity type. A first epitaxial layer of silicon carbide 12 is on the substrate 11 and has the same conductivity type as the substrate. A second epitaxial layer 13 is on the first epitaxial layer and has the opposite conductivity type from the first layer. As a result, the first and second epitaxial layers 12 and 13 form a p-n junction therebetween. Ohmic contacts 14 and 15 respectively complete the structure for providing the current injected across the junction to produce light from the diode.

Figure 1 schematically shows that in the first embodiment of the invention, the second epitaxial layer 13 has sidewalls designated at 16, and a top surface designated at 17. The second epitaxial layer 13 has a thickness sufficient to increase the solid angle at which light emitted by the junction will radiate externally from the sidewall 16, but less than the thickness at which internal absorption in the layer 13 would substantially reduce the light emitted from the top surface 17 of the diode.

As is known to those familiar with the basic principles of optics, the extent to which light will be reflected or refracted at the surface of a material is a function of the refractive index of the material to the particular wavelength of light and the refractive index of the adjacent material to light of that wavelength. These properties define a critical angle using the well-known relationship of Snell's Law. Summarized briefly, Snell's Law defines a critical

-6-

angle for any two adjacent materials, based upon their respective indexes of refraction. The critical angle is defined as the angle between the direction of propagation of the light, and a line normal to the boundary at the point the light strikes the boundary. When light strikes the boundary between the materials at an angle less than the critical angle, it changes direction somewhat (i.e., it refracts), but is nevertheless emitted. If the light strikes the boundary at an angle greater than the critical angle, however, the light is totally internally reflected rather than emitted.

Because light from an LED is generated at the junction, the amount of light that will be emitted from the top surface 17 of the diode is limited by total internal reflection, which, as stated above, is determined by the critical angle defined by Snell's Law and the refractive indexes of the semiconductor and the surrounding medium. As is known to those familiar with light-emitting diodes, the surrounding medium will usually be either a plastic material, or the ambient surroundings; i.e., air. Light rays that are incident on the top surface 17 at an angle less than the critical angle are transmitted. The remaining light rays are reflected back into the device where most are absorbed.

Alternatively, the amount of light emitted from the sides of the diode is determined by both the total internal reflection and by the thickness of the second layer 13. Light rays that strike the sidewalls 16 at angles less than the critical angle will be transmitted. Nevertheless, if the layer 13 is relatively thin (e.g., 1 or 2 microns as set forth in the '497 and '168 patents), some light rays heading towards the sidewalls will instead be totally internally reflected off the top surface of the diode and will be absorbed in the substrate before they reach

-7-

one of the sidewalls 16. As an approximation, where a ray of light is considered to have begun at a point source and headed toward a given sidewall, the proportion of transmitted light can be roughly

5 estimated by the solid angle of intersection between the sidewall 16 of the second layer 13 and the cone of radiation for sideways-directed light. The total light from the sidewalls of the diode would then be the sum of the solid angles for all of the points on the entire

10 light-emitting area of the junction for each of the sidewalls 16. A thorough discussion of these principles is set forth in Huang, et al., "Two-Fold Efficiency Improvement in High Performance AlGaInP Light-Emitting Diodes in the 555-620 nm Spectral Region

15 Using a Thick GaP Window Layer," *Appl. Phys. Lett.* 61(9), Aug. 31, 1992, pp. 1045-1047.

As further known to those familiar with the interaction between light and materials, any given material through which light passes will absorb some of

20 the light. The amount absorbed is based on the wavelength of the light, the absorption coefficient of the material (usually expressed in units of reciprocal length; e.g. cm^{-1}), and the distance the light travels through the material. Accordingly, although a thicker

25 top epitaxial layer offers more external emission as described herein, the optimum thickness is limited by the corresponding absorption of the layer.

Figures 7-9 illustrate this effect. Figure 7 illustrates that the radiant flux of two diodes

30 according to the present invention increases with an increase in the thickness of the top epitaxial layer up to a maximum, and then begins to decrease as the layer becomes too thick and the effects of absorption begin to overtake the benefits of the thicker layer. As

35 indicated in Figure 7, one diode had a 6.8 mil by 6.8 mil mesa, and the other had an 8.0 mil by 8.0 mil mesa. Figures 8 and 9 illustrate how the absorption

-8-

coefficients for n-type and p-type silicon carbide increase as the dopant concentration (in cm^{-3}) increases.

In preferred embodiments of the present invention, the thickness of the second layer 13 is on the order of about 25 microns, a large increase over prior commercial devices for which such thicknesses are typically on the order of 1-3 microns. Figure 6 shows how the increase in the surface layer 13 thickness increases the light output of a device according to the invention. In Figure 6, the output of a device with a 3 micron surface layer is taken as a baseline value of 100%. The increased light output resulting from increased surface p-layer thickness is then plotted as a function of thickness. As demonstrated by Figure 6, the increase in the thickness of the second layer 13 has a very effective positive impact on the light output of the device. To date, a thickness of about 25 microns has been found to be appropriate.

Figure 1 illustrates a further aspect of the present invention, reflective contacts. Figure 1 illustrates the ohmic contact to the substrate as a deposited metal 14. As is known to those familiar with such materials, in order to get appropriate ohmic behavior, the metal of the ohmic contact 14 must normally be alloyed or annealed after being deposited on the appropriate substrate, epitaxial layer, or other portion of the device 10. Such alloying or annealing, however, tends to reduce the reflectivity that a deposited metal will normally exhibit. For example, aluminum, when deposited on silicon carbide, but not annealed or alloyed, will exhibit a reflectivity of 90% or more. As deposited, however, aluminum generally will not exhibit ohmic behavior with respect to silicon carbide. Thus, in devices to date, reflectivity must be sacrificed in exchange for ohmic behavior. In turn, light generated by the diode that strikes the

-9-

unreflective contact will tend to be absorbed rather than reflected or emitted.

The invention, however, further increases the external efficiency of the LED by incorporating a
5 reflective metal deposit as an ohmic contact which remains unalloyed and unannealed and therefore maintains its reflectivity.

As illustrated in Figure 1, the reflective metal, such as aluminum, is deposited upon a very thin
10 layer 18 that forms a top portion of the LED 10. The layer 18 is highly doped and is between the reflective metal deposit 15 and the diode, in particular the second layer 13. The highly doped layer has the same conductivity type as the portion of the diode to which
15 it is adjacent, in this case the same conductivity type as the second layer 13. The highly doped layer 18 has a dopant concentration sufficient to lower the barrier between the metal contact 15 and the second layer 13 enough to provide ohmic behavior between the unannealed
20 reflective metal and the diode. As a result, at least one of the ohmic contacts, and potentially both of them, can comprise an unannealed metal contact, such as the contact 15, which forms a reflective surface from which light generated by the diode will reflect rather
25 than be absorbed. Although it will be recognized that the reflected light generated at the junction will be reflected back into the epitaxial layers 12 and 13, the fact that they are reflected at all, rather than simply absorbed, increases the amount of such light that will
30 eventually escape from either the top surface 17 or the sidewalls 16 of the LED 10. To date, the use of reflective contacts in this manner has resulted in increases as great as 50% in the overall efficiency of the devices as compared to prior LEDs.

35 A thorough discussion of a method of producing an ohmic contact in this manner is set forth in copending application Serial No. 07/943,043; filed

-10-

September 10, 1992 by Glass et al for "Method of Forming Ohmic Contacts to p-Type Wide Bandgap Semiconductors and Resulting Ohmic Contact Structure," the contents of which are incorporated entirely herein
5 by reference. In preferred embodiments of the invention the dopant concentration of the highly doped layer is greater than about $2E19$ ($2 \times 10^{19} \text{ cm}^{-3}$), and most preferably is greater than about $5E19$ ($5 \times 10^{19} \text{ cm}^{-3}$).

10 In the present invention, preferred metals for the ohmic contacts, including the reflective contacts, are aluminum, gold, platinum, and silver. Similarly, the preferred polytypes for the silicon carbide are the 6H, 4H, and 15R polytypes.

15 Some further features of the invention are shown in the embodiment illustrated in Figure 2 in which the LED is broadly designated at 20. Figure 2 illustrates a silicon carbide single crystal substrate 21 having a first conductivity type. A first epitaxial
20 layer is formed of a compensated layer 22 and a predominantly uncompensated layer 23.

As used herein, the term "compensated" refers to a portion of semiconductor material doped with both donor and acceptor dopants. Thus, a compensated p-type
25 layer would include both p-type and n-type dopants, but with a sufficient excess of the p-type dopants to give the layer p-type characteristics overall. The reasons for using compensated layers in silicon carbide LEDs are set forth in an appropriate manner in the '497 and
30 '168 patents already incorporated herein by reference.

As illustrated in Figure 2, the substantially uncompensated layer 23 is adjacent to substrate 21 while the compensated layer 22 is adjacent an intermediate epitaxial layer 24 which has a
35 conductivity type opposite from the conductivity type of layers 22, 23, and 21. The epitaxial layers 24 and 22 form a p-n junction from which light is emitted when

-11-

a potential difference is applied across the diode 20. The second epitaxial layer 25 is on the intermediate epitaxial layer 24 and has the same conductivity type as the intermediate epitaxial layer 24. As in the
5 first embodiment, the second layer 25 has sidewalls 26 and a top surface 27 that forms the top surface of the diode 20. The second epitaxial layer 25 has a thickness sufficient to increase the solid angle at which light emitted by the junction will radiate
10 externally from the sidewalls 26, but less than the thickness at which internal absorption in the layer 25 would substantially reduce the light emitted from the top surface 27 of the diode.

As stated above, the first epitaxial layer is
15 formed by respective compensated and uncompensated layers 22 and 23, with the predominantly uncompensated layer 23 being adjacent to substrate 21. The intermediate epitaxial layer 24 is likewise compensated so that injection of carriers across the junction
20 between layers 24 and 22 takes place between compensated portions of silicon carbide to give the appropriate energy transitions and wavelengths as described in the '497 and '168 patents.

In a preferred embodiment, and to obtain a
25 peak wavelength in the 460-475 nm range (and preferably 465-470 nm), the substrate 21 and layers 22 and 23 are of n-type conductivity, while the intermediate epitaxial layer 24 and the second epitaxial layer 25 are p-type conductivity. In a most preferred
30 embodiment, the second layer 25 and the uncompensated layer 23 are doped slightly more heavily than their respective adjacent layers 24 and 22 in a manner which encourages the proper transition of carriers across the junction. Figures 3 and 4 illustrate these
35 characteristics, with Figure 3 showing the peak wavelengths and Figure 4 showing radiant flux and external power efficiency, both as a function of

-12-

forward current in milliamps. The undotted lower curve in Figure 4 represents the performance of prior diodes not specifically incorporating the features of the present invention.

- 5 In other embodiments, and for which a slightly different wavelength of blue light is desired, layers 22 and 23, and the substrate 21 can be of p-type conductivity while layers 24 and 25 can be of n-type conductivity. Preferably, the second layer 25 is
10 predominantly uncompensated as is the substrate.

Figure 2 further illustrates that in preferred embodiments, the epitaxial layers 22 through 25 form a mesa structure upon the substrate 21.

- In the embodiment illustrated in Figure 2,
15 the reflective metal contact is designated at 30, and is made to the semiconductor 21. The heavily doped layer that permits the ohmic contact is likewise illustrated as 31. It will be understood that the use of reflective contacts and the appropriate highly doped
20 layer can be made to one or both of the ohmic contacts to the device 20.

- In another embodiment, where the LED is to be placed in a plastic carrier material, as is quite common for such devices, the thickness of the second
25 layer 25 is less than the thickness at which internal absorption in the layer would substantially reduce the light emitted from the top surface of the diode.

- Figure 2 illustrates another embodiment of the invention in which one or more of the contacts are
30 formed of a substantially transparent conductive material. In Figure 2, the transparent contact is illustrated at 32 and is preferably formed of an indium-tin-oxide (ITO) material which is useful for transparent contacts in electro-optical applications in
35 a manner well known to those familiar with this art. Any other compounds having similar transparent characteristics would likewise be acceptable, provided

-13-

that they can carry enough current to drive the LED without being applied in such thicknesses that their transparency would be reduced beyond the point at which the transparent contact would be advantageous. As in
5 the case of the reflective contact of the present invention, it will be understood that the transparent contact can be used for one or both of the contacts to an LED, and can be used in combination with either the reflective contact or a more typical annealed or
10 alloyed ohmic contact. Typically, an ITO contact is used in conjunction with a contact pad (not shown) of a more conventional metal or other conductor.

In yet another embodiment, the invention comprises an LED in which the cross-sectional area of
15 the top surface, as indicated at 17 in Figure 1 and at 27 in Figure 2, is similarly increased. In preferred embodiments, the cross-sectional area is increased from approximately 170 by 170 square microns of a typical LED to approximately 200 by 200 square microns.
20 Increasing this parameter has given increases of at least 7% in present devices. Figure 5 illustrates the increase in light output of a blue LED formed in silicon carbide when the mesa area is increased.

In this regard, the use of a wider mesa in
25 conjunction with a thicker "window layer" has synergistic advantages. As stated above, silicon carbide, particularly p-type, tends to be somewhat resistive. Thus, an applied current spreads in a less than ideal manner throughout the epitaxial layers.
30 Making the mesa wider as well as thicker increases the opportunity for current to spread when a potential difference is applied across the diode. The greater area of the diode gives the current more initial room to spread, and the deeper window layer adds for even
35 further lateral spreading as the current moves axially through the diode. The result is a greater flow of current through the diode and across the junction to

-14-

produce a greater amount of visible light. Thus, in addition to providing advantages on an individual basis, the wider mesa and deeper window layer provide a synergistic effect that increases the external quantum efficiency of the resulting diode even more.

In yet another embodiment, the invention provides a method of forming a reflective ohmic contact on a silicon carbide light-emitting diode to thereby increase the light emitted externally from the diode.

10 The method comprises applying a metal to a surface portion of the silicon carbide diode and in which the portion of the diode having the surface is a highly doped layer of silicon carbide, and wherein the highly doped layer has a dopant concentration sufficient to

15 lower the barrier between the metal contact and the diode portion enough to provide ohmic behavior between the metal and the diode portion. In preferred embodiments, the method can further comprise the step of heating the applied metal sufficiently to improve

20 the ohmic characteristics of the metal contact, but less than the amount of heating that would substantially reduce the reflectivity of the applied metal.

In preferred embodiments, the step of

25 applying the metal can comprise sputtering or evaporation techniques.

In use, the various aspects of the invention have given significant increases. For example, increasing the standard thickness of the top epitaxial

30 layer from 3 microns to approximately 25 microns increases the external output of the LED by at least about 30%. Increasing the surface area from 170 by 170 square microns to 200 by 200 square microns increases the external output approximately 7%. Adding a

35 reflective contact rather than an annealed or opaque contact gives a 50% increase in external output. When combined, all of these improvements have increased the

-15-

efficiency of blue LEDs, according to the present invention, nearly 100% over earlier devices such as those described in the '497 and '168 patents.

In the drawings and specification, there have
5 been disclosed typical preferred embodiments of the invention and, although specific terms have been employed, they have been used in a generic and descriptive sense only and not for purposes of
10 limitation, the scope of the invention being set forth in the following claims.

-16-

THAT WHICH IS CLAIMED IS:

1. A light emitting diode that emits light in the blue portion of the visible spectrum with high external quantum efficiency, said diode comprising:
 - a single crystal silicon carbide substrate
 - 5 having a first conductivity type;
 - a first epitaxial layer of silicon carbide on said substrate and having the same conductivity type as said substrate;
 - a second epitaxial layer of silicon carbide
 - 10 on said first epitaxial layer and having the opposite conductivity type from said first layer,
 - said first and second epitaxial layers forming a p-n junction; and
 - ohmic contacts for applying a potential
 - 15 difference across said p-n junction;
 - characterized in that:
 - said second epitaxial layer has side walls and a top surface that forms the top surface of said diode, and said second epitaxial layer has a thickness
 - 20 sufficient to increase the solid angle at which light emitted by the junction will radiate externally from said side walls, but less than the thickness at which internal absorption in said second layer would substantially reduce the light emitted from said top
 - 25 surface of the diode.
2. A light emitting diode according to Claim 1 wherein said second epitaxial layer has a thickness of about 25 microns and said top surface has an area of about 200 by 200 square microns.
- 30 3. A light emitting diode according to Claim 1 wherein the silicon carbide has a polytype selected from the group consisting of the 6H, 4H, and 15R polytypes.

-17-

4. A light emitting diode according to Claim 1 wherein at least one of said ohmic contacts comprises a layer of indium-tin-oxide (ITO) on said second epitaxial layer, said ITO layer having a thickness
5 sufficient to carry current to said second layer sufficient for said diode to emit light, but thin enough to remain substantially transparent.

5. A light emitting diode according to Claim 1 and further comprising an intermediate epitaxial
10 layer of silicon carbide between said first and second epitaxial layers, said intermediate epitaxial layer having a compensated conductivity type opposite from the conductivity type of said first layer so that said first epitaxial layer and said intermediate epitaxial
15 layers form said p-n junction.

6. A light emitting diode according to Claim 5 wherein said first epitaxial layer further comprises a compensated layer adjacent said compensated second epitaxial layer, and a predominantly uncompensated
20 layer adjacent said substrate.

7. A light emitting diode according to Claim 5 wherein said second layer is predominantly uncompensated.

8. A light emitting diode according to Claim 5 wherein said substrate is predominantly
25 uncompensated.

9. A light emitting diode according to Claim 5 wherein said epitaxial layers form a mesa structure upon said substrate.

-18-

10. A light emitting diode according to Claim 5 wherein one of said ohmic contacts comprises an unannealed metal contact adjacent said second layer, said metal contact forming a reflective surface from which light generated by said diode will reflect rather than be absorbed.

11. A light emitting diode according to Claim 10 wherein said metal contact is selected from the group consisting of aluminum, gold, platinum, and silver.

12. A light emitting diode according to Claim 10 and further comprising a highly doped layer between said second layer and said unannealed metal contact, said highly doped layer having the same conductivity type as said second layer, and said highly doped layer having a dopant concentration sufficient to lower the barrier between said metal contact and said second epitaxial layer sufficiently to provide ohmic behavior between said unannealed metal and said second epitaxial layer, said highly doped layer being thin enough to prevent the dopant concentration from substantially reducing the light emitted from said top surface of said second epitaxial layer.

13. A light emitting diode according to Claim 5 wherein one of said ohmic contacts comprises an unannealed metal contact adjacent said substrate, said metal contact forming a reflective surface from which light generated by said diode will reflect rather than be absorbed.

14. A light emitting diode according to Claim 13 and further comprising a highly doped layer between said substrate and said unannealed metal contact, said highly doped layer having the same

-19-

conductivity type as said substrate, and said highly doped layer having a dopant concentration sufficient to lower the barrier between said metal contact and said substrate sufficiently to provide ohmic behavior

- 5 between said unannealed metal and said substrate, said highly doped layer being thin enough to prevent the dopant concentration from substantially reducing the light emitted from said substrate.

15. A light emitting diode according to
10 Claim 13 wherein said metal contact is selected from the group consisting of aluminum, gold, platinum, and silver.

16. A light emitting diode according to
Claim 10 wherein said metal contact has been heated
15 sufficiently to improve the ohmic characteristics of said metal contact, but less than the amount of heating that would substantially reduce the reflectivity of said metal contact.

1/5

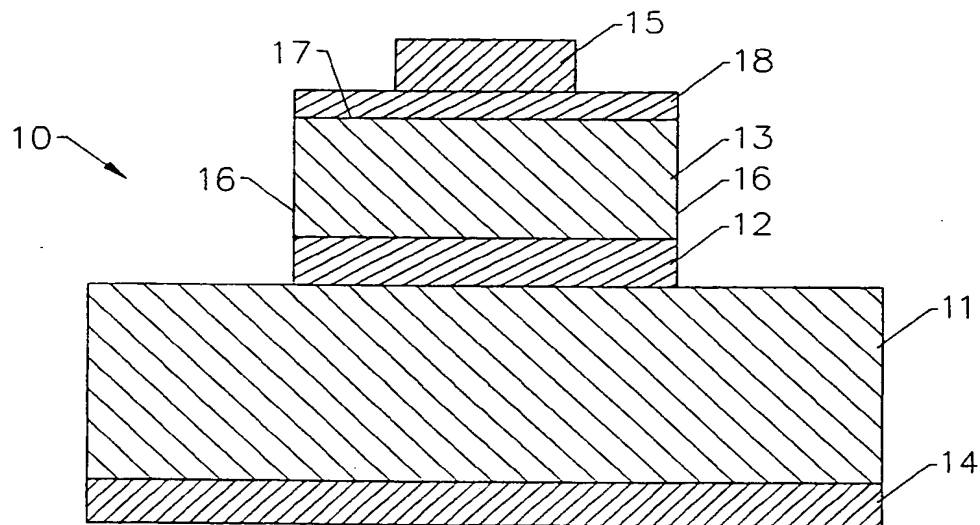


FIG. 1.

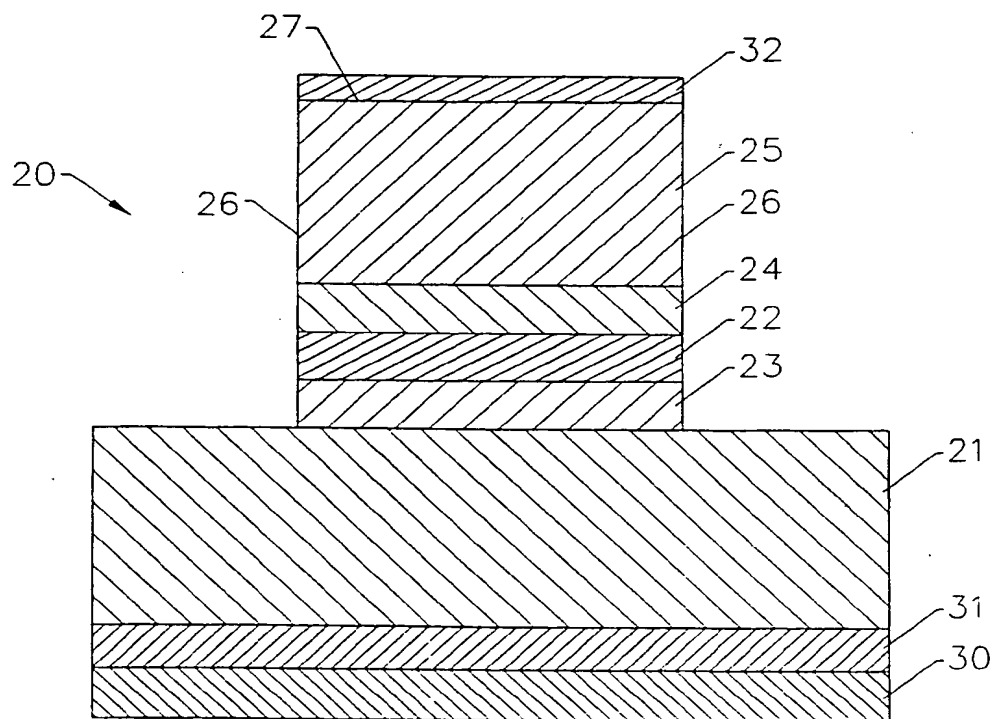


FIG. 2.

SUBSTITUTE SHEET (RULE 26)

2/5

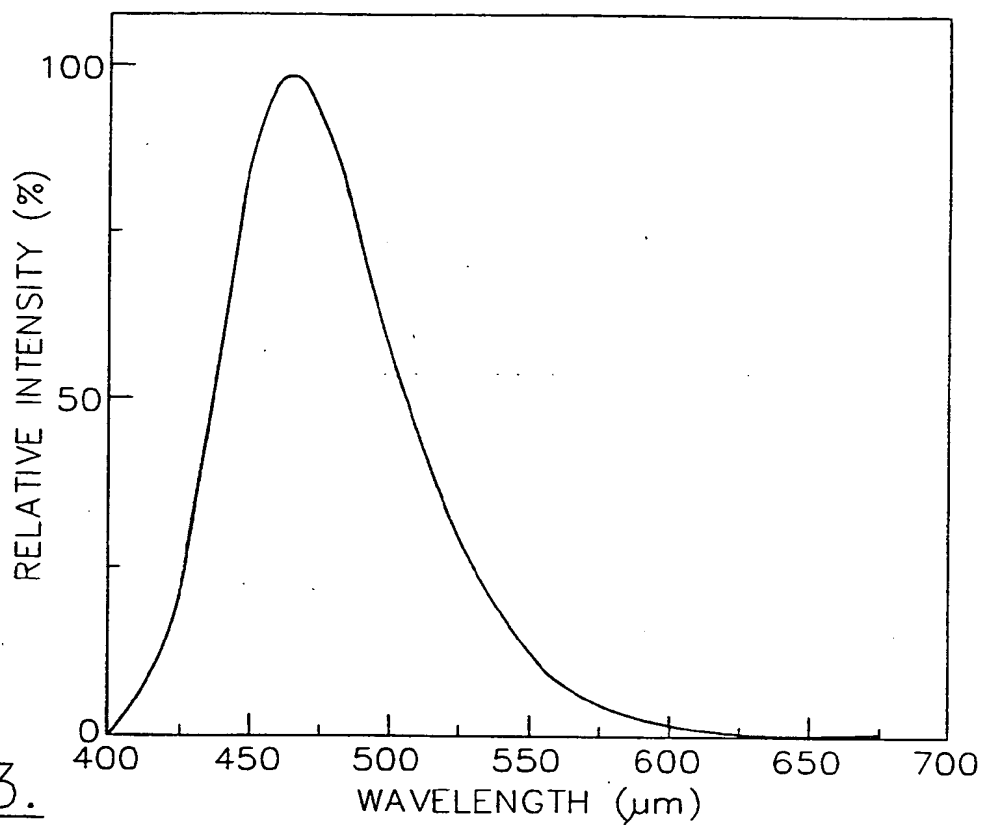


FIG. 3.

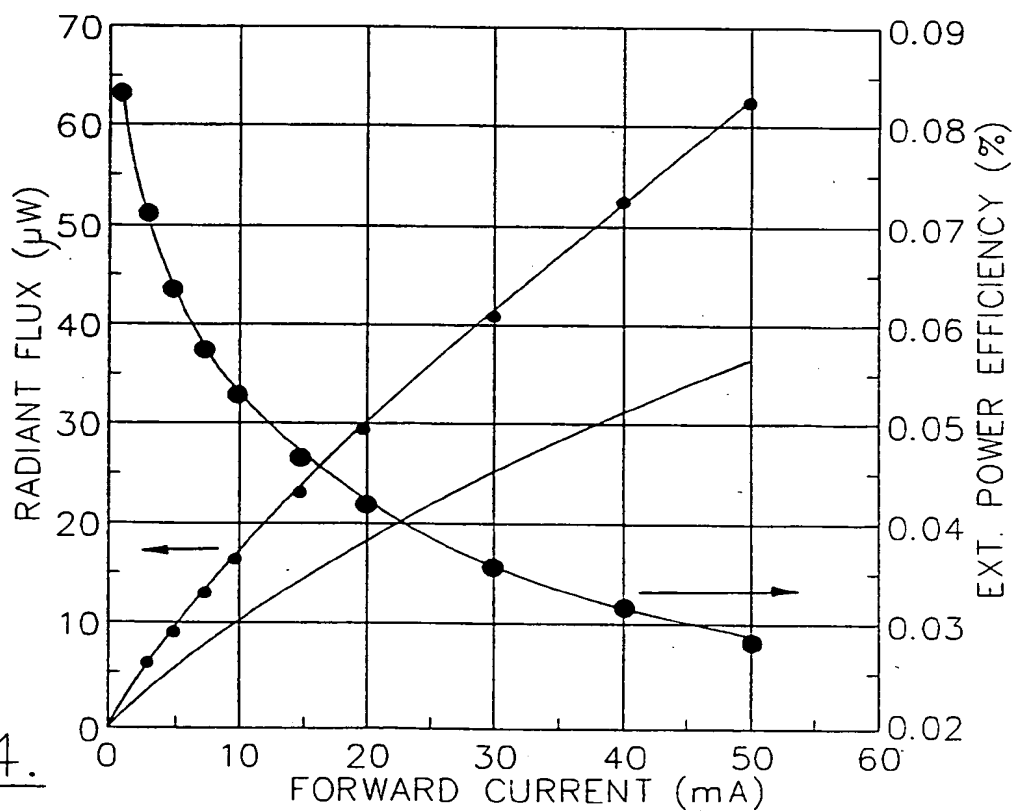
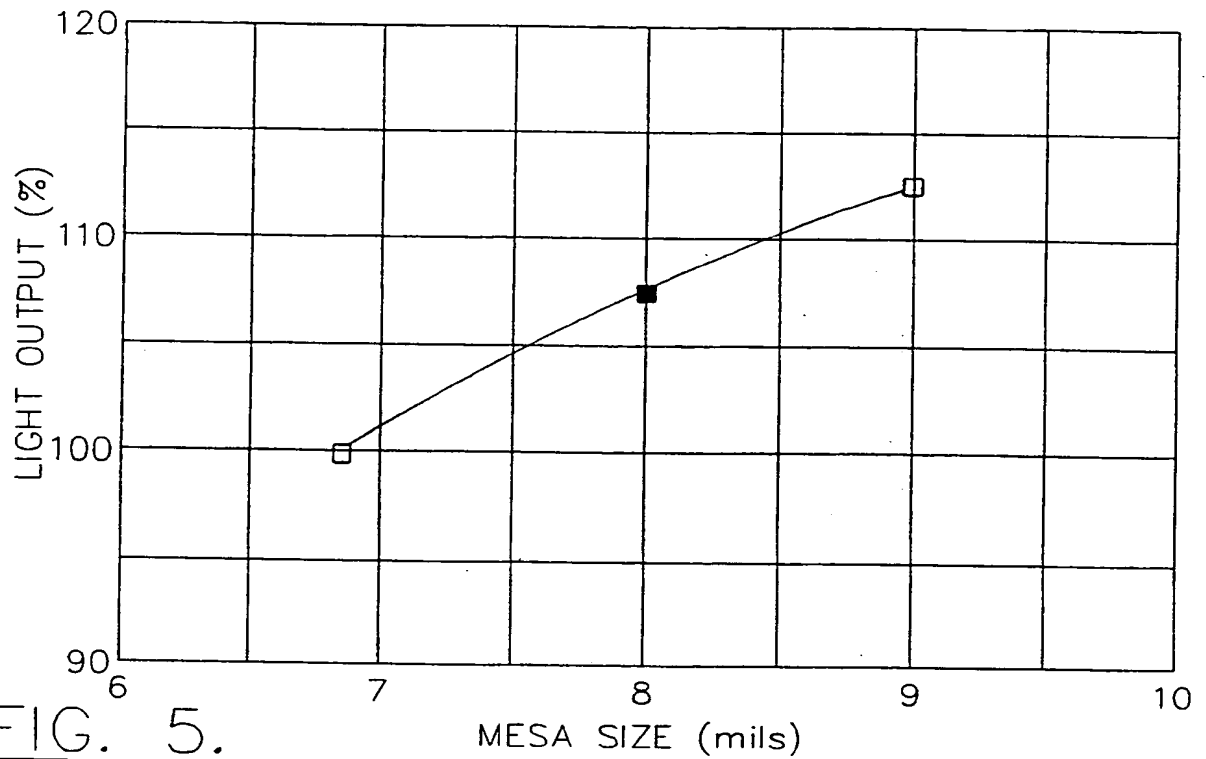
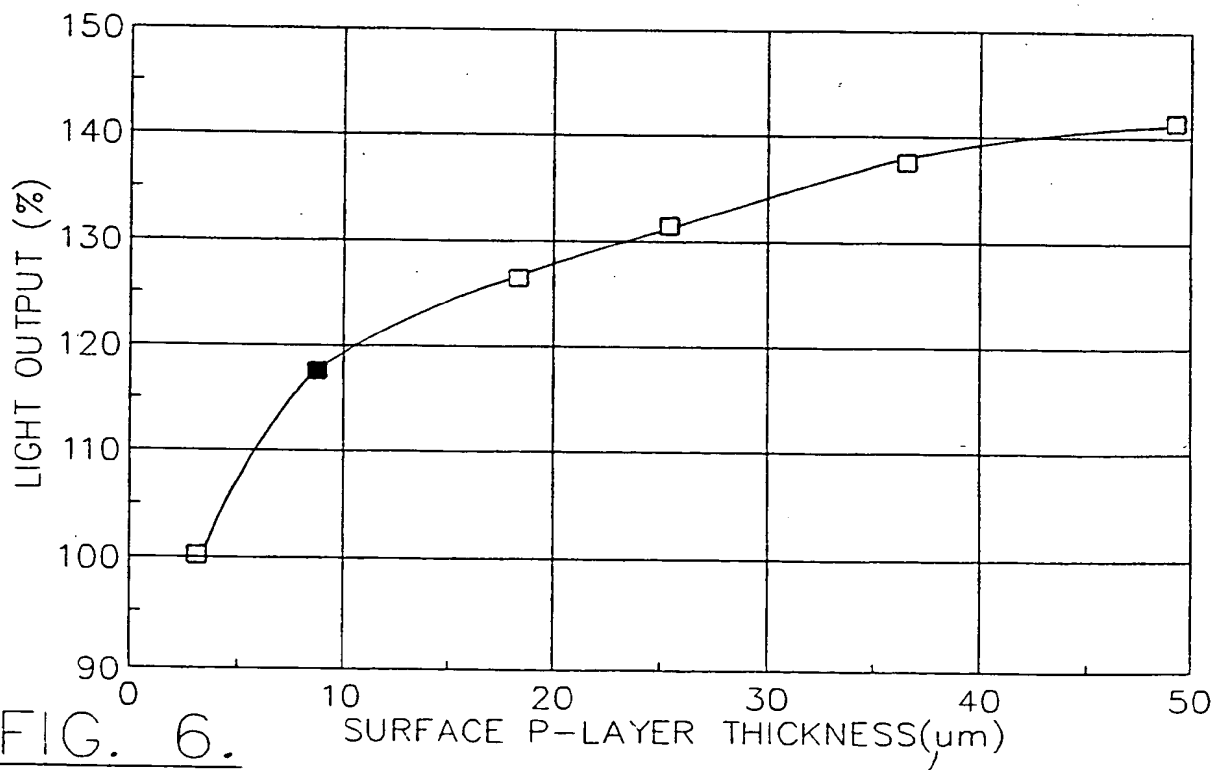
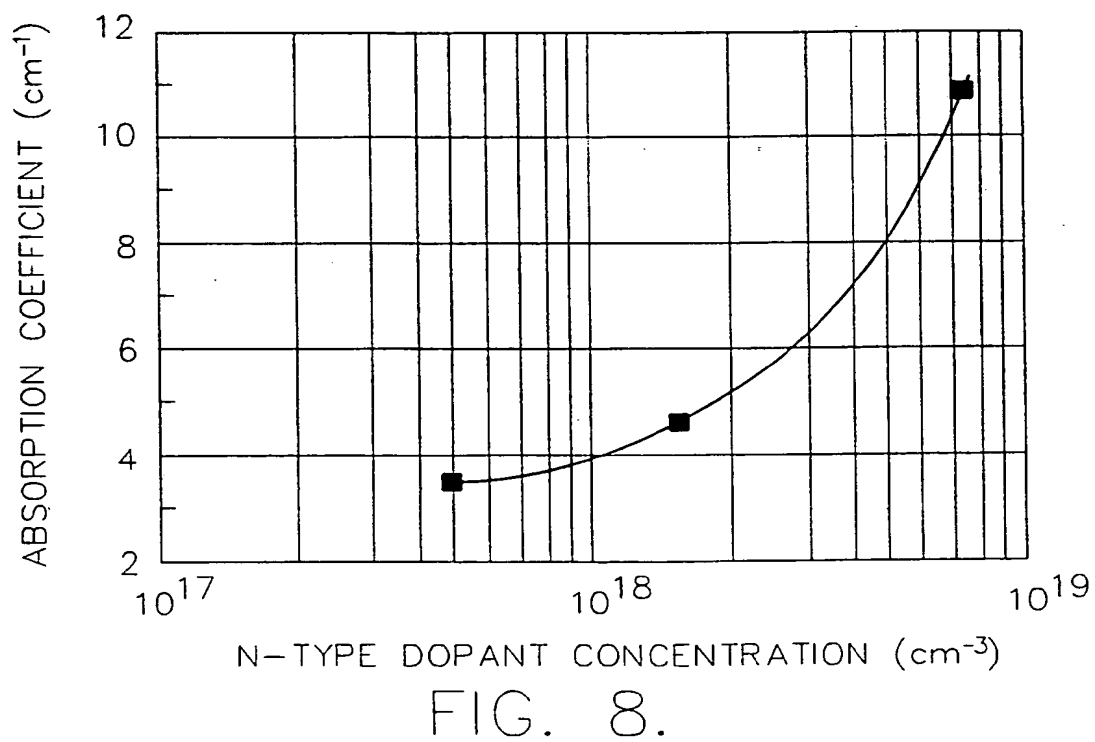
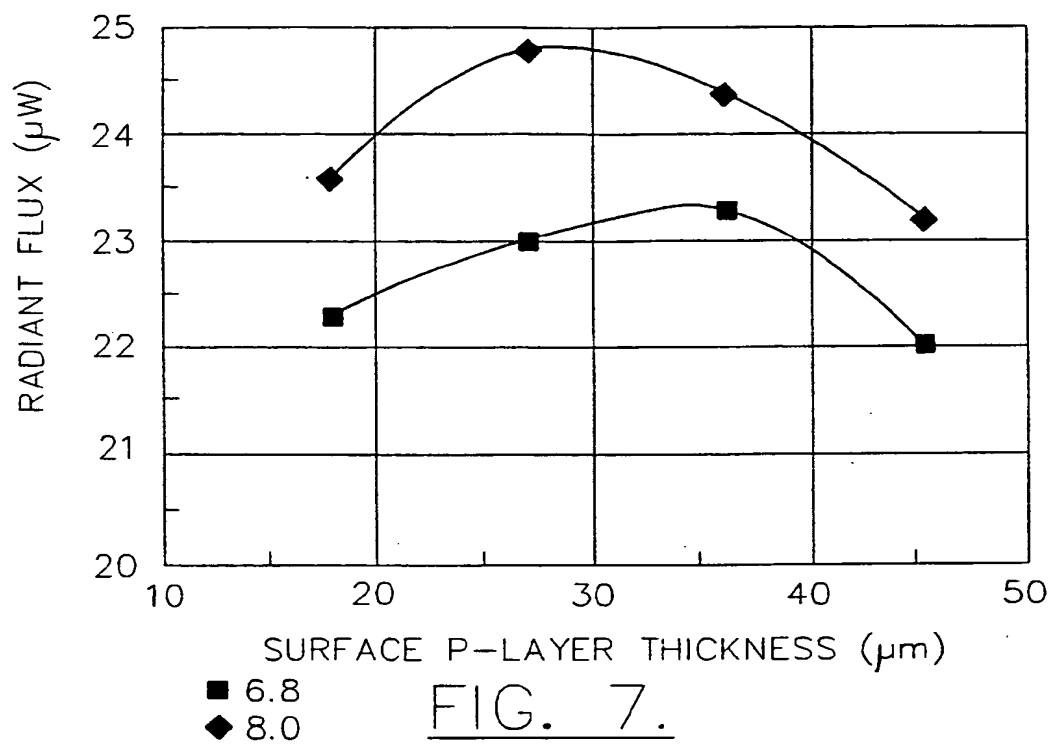


FIG. 4.

3/5

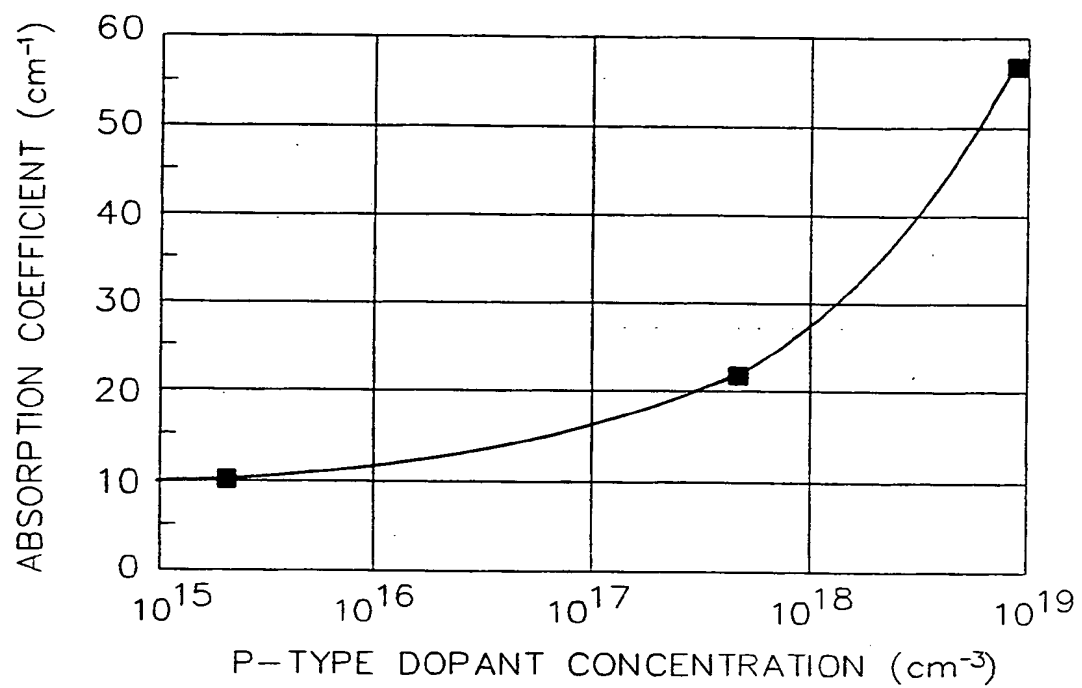
FIG. 5.FIG. 6.

4/5



SUBSTITUTE SHEET (RULE 26)

5/5

FIG. 9.

SUBSTITUTE SHEET (RULE 26)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 94/04497

A. CLASSIFICATION OF SUBJECT MATTER
IPC 5 H01L33/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 5 H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	SOVIET TECHNICAL PHYSICS LETTERS., vol.11, no.2, February 1985, NEW YORK US pages 101 - 102 V.A. DMITRIEV ET AL 'Silicon carbide light-emitting diodes for the blue-violet region' see the whole document ---	1-3,9
X	JOURNAL OF APPLIED PHYSICS, vol.50, no.12, December 1979, NEW YORK US pages 8215 - 8225 M. IKEDA ET AL. 'Fabrication of 6H-SiC light-emitting diodes by a rotation dipping technique: Electroluminescence mechanisms' see page 8215 - page 8216 --- -/--	1-3

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents :

- "A" document defining the general state of the art which is not considered to be of particular relevance
- "E" earlier document but published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed

- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
- "&" document member of the same patent family

Date of the actual completion of the international search

13 September 1994

Date of mailing of the international search report

27.09.94

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+ 31-70) 340-2040, Tx. 31 651 epo nl,
Fax (+ 31-70) 340-3016

Authorized officer

Visentin, A

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 94/04497

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO,A,90 07196 (CREE RESEARCH INC.) 28 June 1990 see claims 1-29; figures 1-8,12 ---	1,3,5,9, 10,13,15
A	PHYSICA B CONDENSED MATTER, vol.185, no.1-4, April 1993, AMSTERDAM, NL pages 453 - 460 J.A. EDMOND ET AL. 'Blue LEDs, UV photodiodes and high temperature rectifiers in 6H-SiC' ---	
A	APPLIED PHYSICS LETTERS., vol.61, no.9, 31 August 1992, NEW YORK US pages 1045 - 1047 K.H. HUANG ET AL. 'Twofold efficiency improvement in high performance AlGaInP light-emitting diodes in the 555-620 nm spectral region using a thick GaP window layer' cited in the application ---	
A	PATENT ABSTRACTS OF JAPAN vol. 17, no. 276 (E-1372) 27 May 1993 & JP,A,05 013 812 (SHARP CORP.) 22 January 1993 see abstract ---	1,4
A	US,A,5 187 547 (T. NIINA ET AL.) 16 February 1993 -----	

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US 94/04497

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO-A-9007196	28-06-90	US-A- 4918497	17-04-90
		US-A- 5027168	25-06-91
		AU-A- 4759290	10-07-90
		CA-A- 2005377	14-06-90
		EP-A- 0448607	02-10-91
		JP-T- 5502546	28-04-93
<hr/>			
US-A-5187547	16-02-93	JP-A- 2290084	29-11-90
<hr/>			

THIS PAGE BLANK (USPTO)

1/5

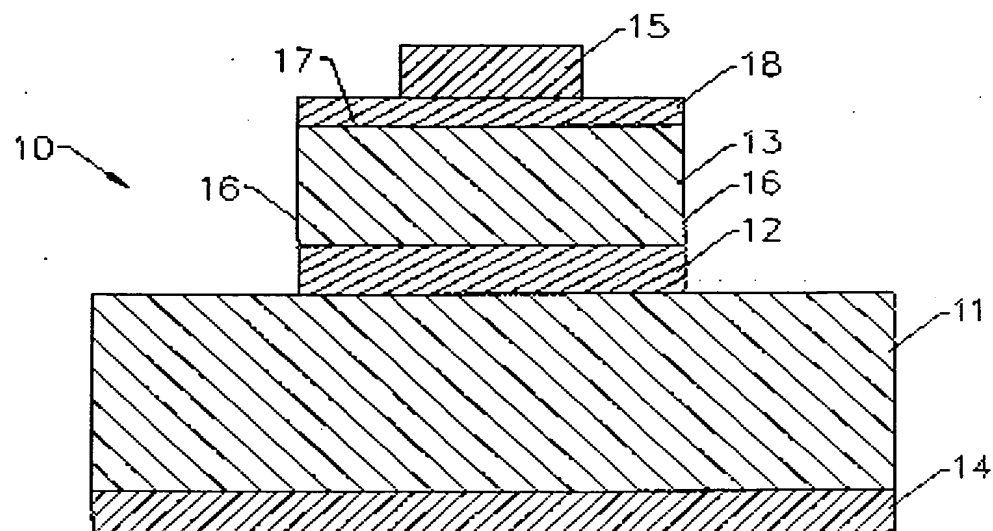


FIG. 1.

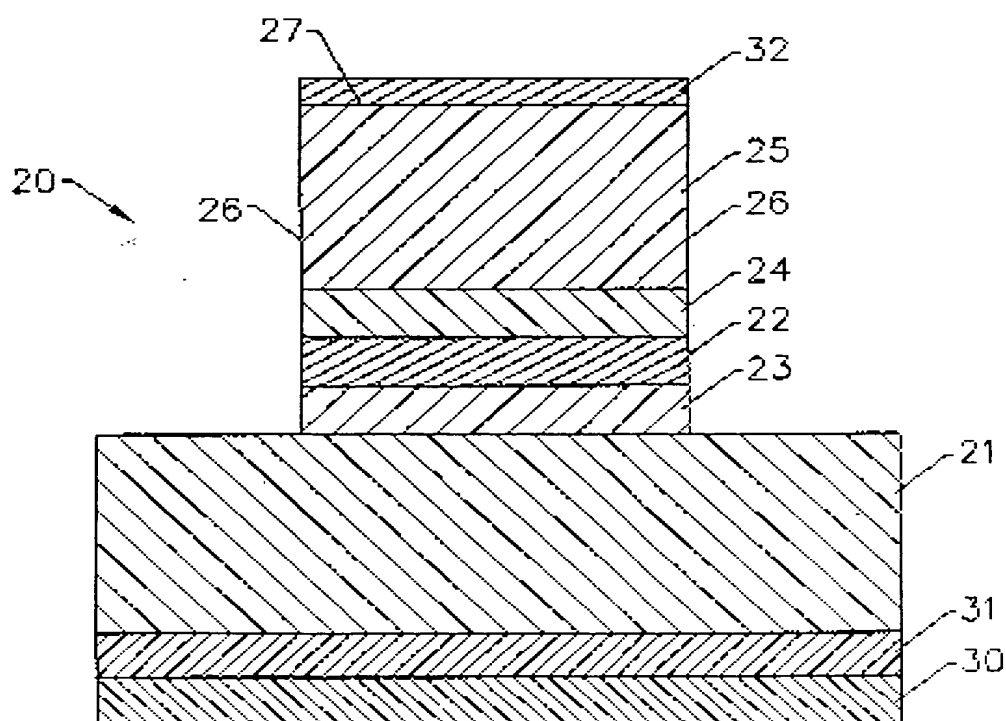


FIG. 2.

SUBSTITUTE SHEET (RULE 26)

2/5

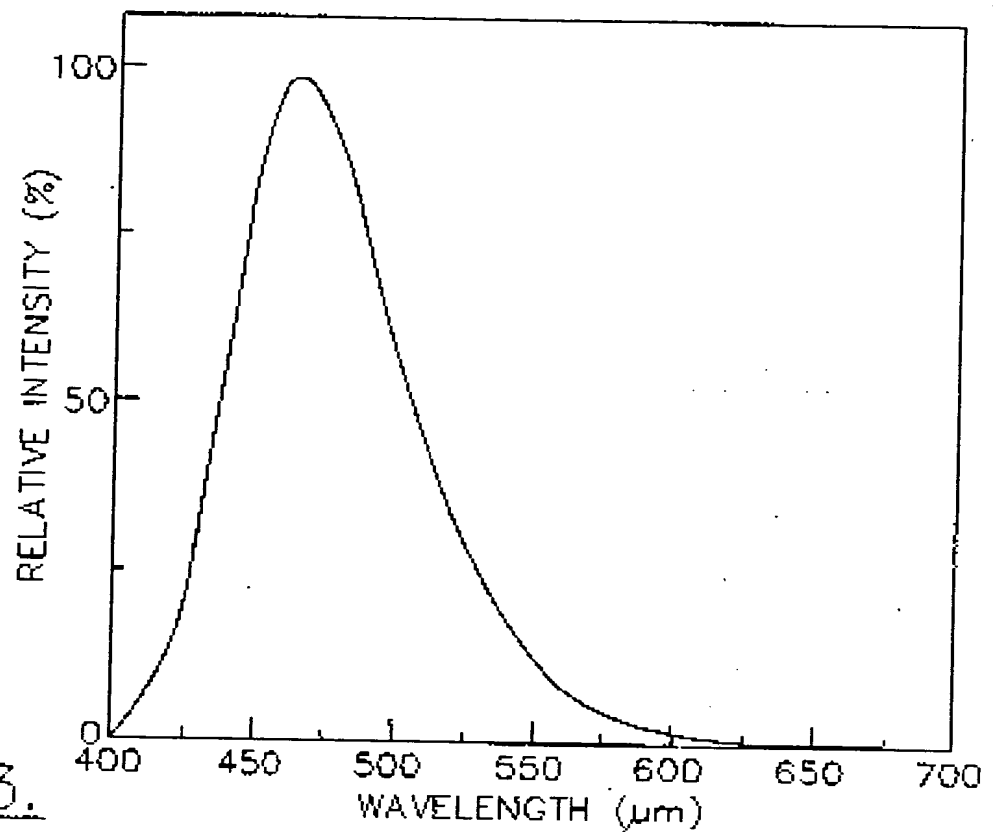


FIG. 3.

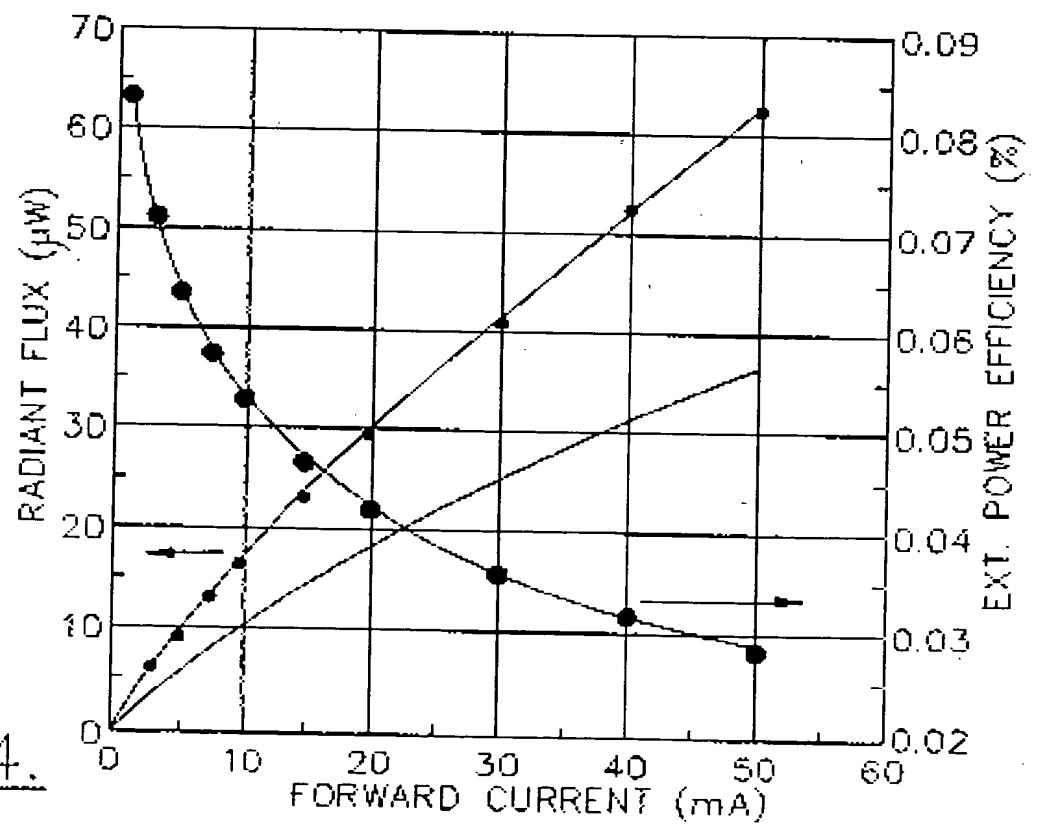
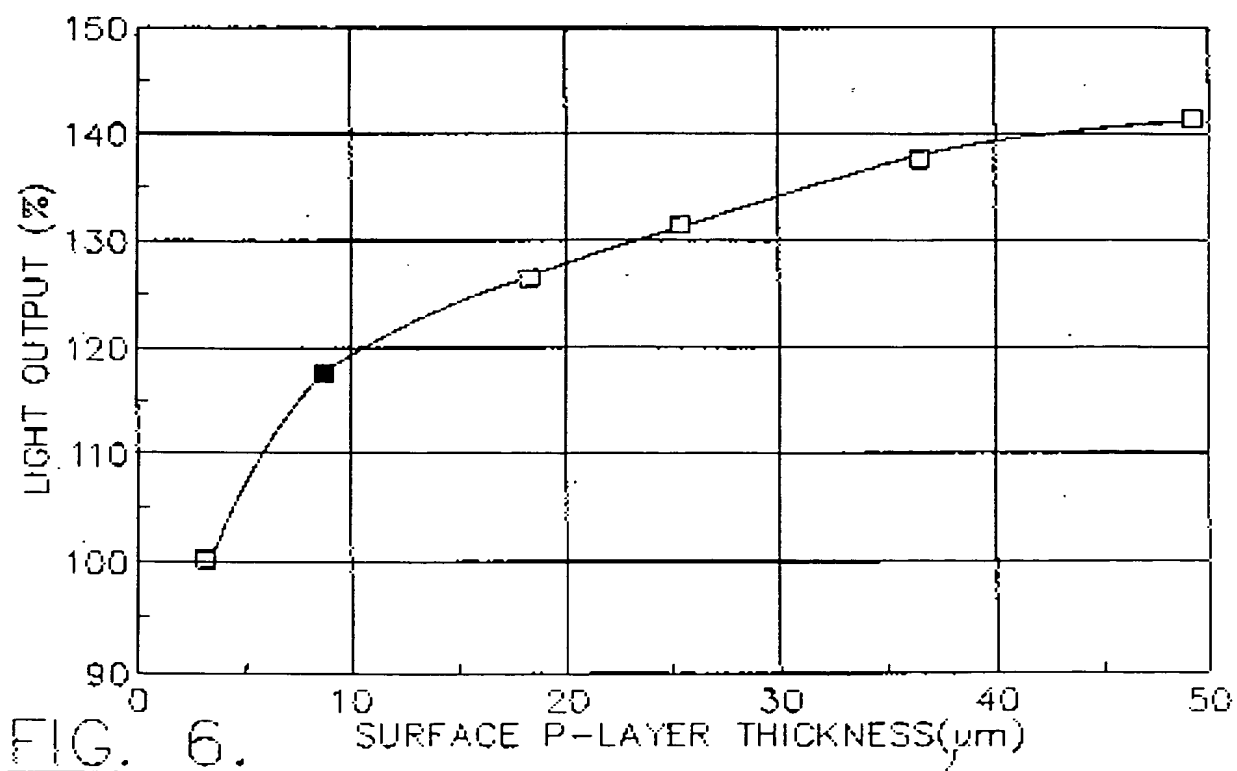
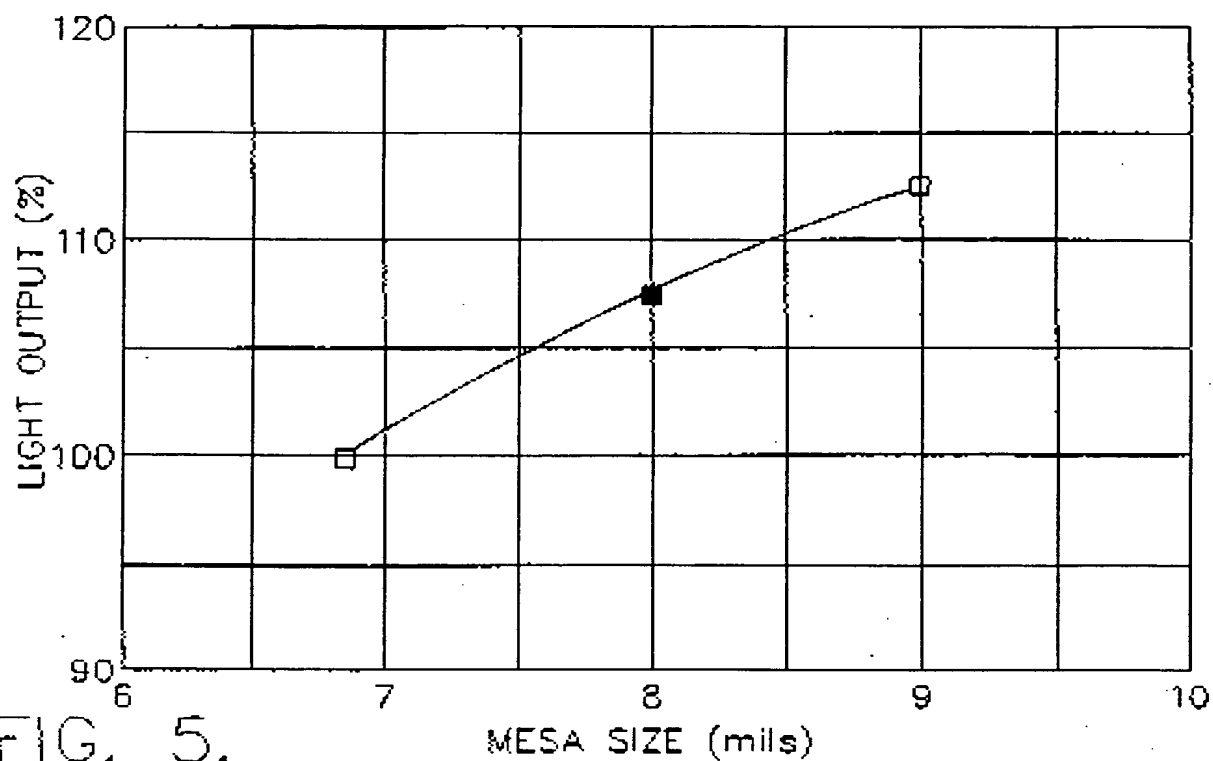


FIG. 4.

3/5



4/5

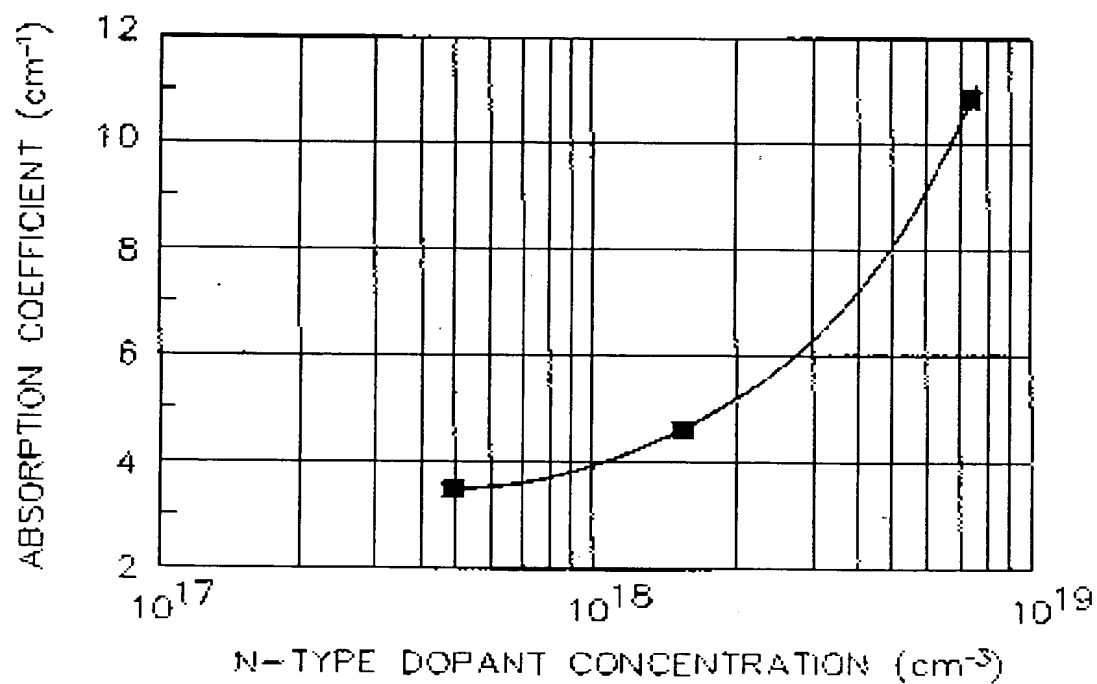
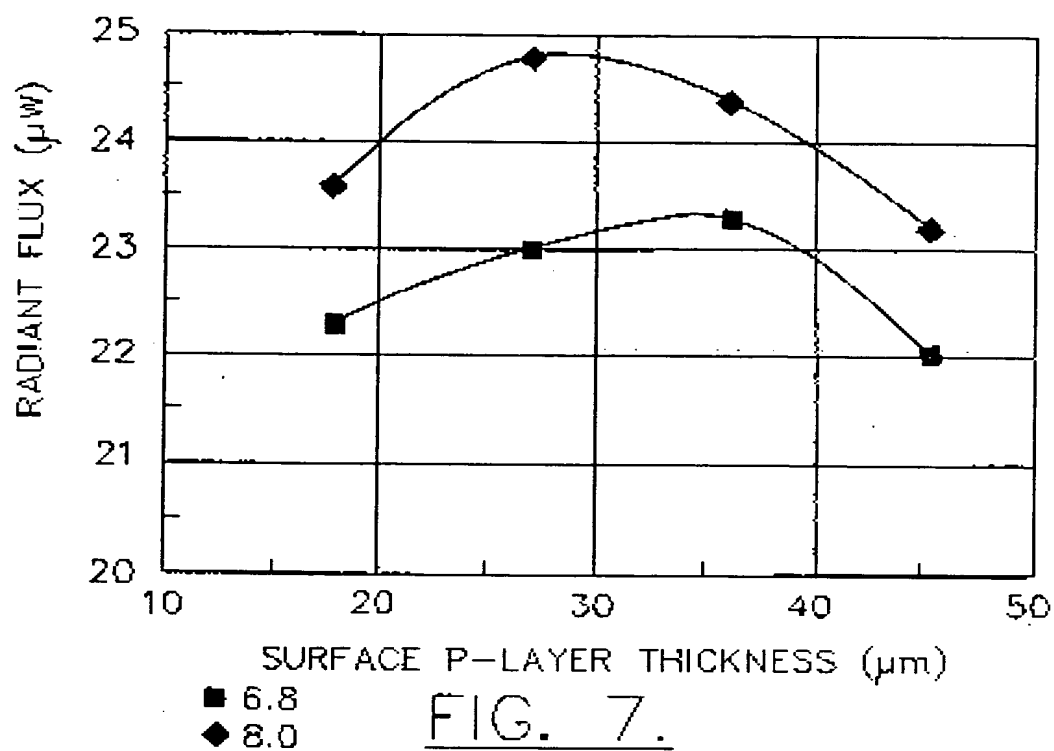
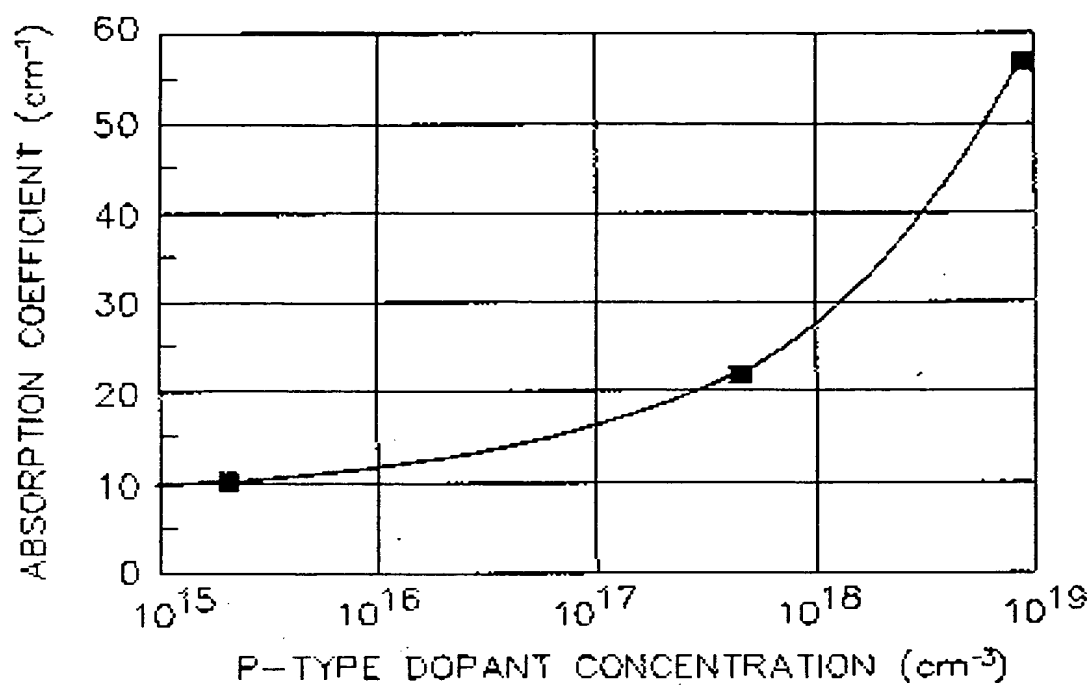


FIG. 8.

SUBSTITUTE SHEET (RULE 26)

5/5

FIG. 9.

SUBSTITUTE SHEET (RULE 26)

THIS PAGE BLANK (USPTO)